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A light bending model for the X–ray temporal and spectral properties of accreting black holes

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ABSTRACT
Some of the X–ray temporal and spectral properties of accreting black holes represent a challenge for current theoretical models. In particular, uncorrelated variability between direct continuum and reflection components (including the iron line, if present) has been reported in many cases. Here, we explore a light bending model in which we assume a primary source of X–rays located close to a central, maximally rotating Kerr black hole and illuminating both the observer at infinity and the accretion disc. We show that, due to strong light bending, the observed flux can vary by more than one order of magnitude as the height of the primary source above the accretion disc varies, even if its intrinsic luminosity is constant. We identify three different regimes in which the reflection–dominated component (and the iron line) is correlated, anti–correlated or almost independent with respect to the direct continuum. These regimes correspond to low, high and intermediate flux states of the X–ray source. As a general rule, the reflection component varies with much smaller amplitude than the continuum. X–ray observations of the Seyfert galaxy MCG–6-30-15 and of the Galactic black hole candidate XTE J1650–500 reveal that a series of predictions of our model are actually observed: the consistent behaviour of the iron line flux and equivalent width (EW) with respect to the direct continuum, as well as the increase of the relative strength of disc reflection as the flux drops, all match very well our predictions. The iron line profile is predicted to be narrower in high flux states and broader in (reflection–dominated) low flux states, in fairly good agreement with observations of the best–studied case of MCG–6-30-15. Observations of some other Narrow Line Seyfert 1 galaxies (e.g. NGC 4051) also seem to support our model, which may explain what are otherwise puzzling characteristics of some sources. We also show that beaming along the equatorial plane can enhance the re–emission of narrow reflection features from distant material during low flux states providing a possible contribution to the observed X–ray Baldwin effect.

Key words: accretion, accretion discs – black hole physics – relativity – X-rays: galaxies – galaxies: active – X-rays: stars

1 INTRODUCTION

The X–ray temporal and spectral properties of a class of active galactic nuclei (AGN) show interesting behaviour that is difficult to understand within the current theoretical view. This is most true for those systems in which reflection spectral components and fluorescent iron lines have been detected. Reflection in AGN is generally believed to be associated with the reprocessing of the primary continuum by cold material in the accretion disc close to the central black hole (George & Fabian 1991; Matt, Perola & Piro 1991) and/or by more distant material, such as the putative torus of unified models (Antonucci 1993).

The presence of broad and redshifted iron lines in some sources indicates that special and general relativistic effects play an important role in producing the line shape, supporting the idea that reflection from the inner regions of an accretion disc is present (Fabian et al. 1989; Laor 1991; Martocchia & Matt 1996; Reynolds & Begelman 1997). However, the variability of the reflection component, and most remarkably of the iron line, is not correlated in a trivial manner to that of the observed continuum. The iron line does not always respond to variations in the continuum as simple reflection models predict. In some cases, an anti–correlation between the iron line and the continuum has been reported; sometimes, the iron line can appear to be constant while the continuum varies with large amplitude (see e.g. Markowitz, Edelson & Vaughan 2003).

Furthermore, the profile of the broad iron line (most remarkably in the Seyfert 1 galaxy MCG–6-30-15) exhibits a singular behaviour: qualitatively, the line tends to be very broad in low flux states, while a narrower core is detected in high flux states (Iwasawa et al. 1996; Wilms et al. 2001; Lee et al. 2002). More-

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over, in many sources, the line equivalent width and the reflection fraction tend to anti–correlate (or, in some cases to remain constant) with the continuum (Lamer, Uttley & M[c]Hardy 2000; Papadakis et al. 2002). If the continuum that we observe is the same that illuminates the disc, these behaviours are difficult to understand.

The uncorrelated variability between the iron line and the continuum may be explained by requiring that it originates from a distant reflector so that the variability of the illuminating continuum is averaged out. However, this interpretation conflicts with the observation of broad and redshifted iron lines in some sources that strongly suggests an origin close to the central black hole (e.g Fabian et al. 2000; Reynolds & Nowak 2003 for a review on iron lines). Alternative explanations for the observed spectra which do not require emission from the inner regions of the accretion disc have been proposed (see e.g. Inoue & Matsumoto 2003).

Here we consider a model based on the gravitational light bending suffered by the radiation emitted in the near vicinity of a rotating black hole with the aim of reconciling the observed puzzling properties of some X–ray sources with the theory of reflection models from accretion discs. We investigate the variability induced by light bending by assuming that the primary source of hard X–rays is centrally concentrated near the axis of a Kerr black hole. Variations in the height of the primary source above the accretion disc produce the bulk of the variability of both the observed continuum and the reflection component (Martocchia, Matt & Karas 2002; Fabian & Vaughan 2003). This idea was presented in Miniutti et al. (2003) and successfully explained the puzzling uncorrelated variability of the broad iron line and continuum seen in a 325 ks *XMM–Newton* observation of the Seyfert 1 galaxy MCG–6-30-15 (Fabian et al. 2002a; Fabian & Vaughan 2003; Vaughan & Fabian 2003). After presenting the main properties and predictions of the light bending model, we review the phenomenology of some X–ray sources, and compare our predictions with the available data.

2 THE LIGHT BENDING MODEL

In this section, we describe the most relevant assumptions and the basic idea of our model for the spectral variability of accreting black hole sources that exhibit a spectral disc reflection component (see also Miniutti et al. 2003).

2.1 Assumptions and computational setup

We assume the presence of a central maximally rotating Kerr black hole with specific angular momentum $a = 0.998$. A geometrically thin accretion disc lies in the hole equatorial plane and matter in the disc is accreted along stable circular geodesics of the Kerr spacetime. The disc extends down to the marginal stable orbit (with radial coordinate $r_{\rm in} = r_{\rm ms} \simeq 1.24\ r_g$) and has an outer radius of $r_{\rm out} = 100\ r_g$. Relativistic effects play a major role only in the near vicinity of the central black hole, so that the inner disc radius is an important parameter of the model, while the outer radius is not expected to have significant effects on our results (see e.g. Martocchia, Karas & Matt 2000).

With this setup, it is clear that the spin parameter of the black hole, which is here assumed maximal, is relevant for our results because it fixes the value of the marginal stable orbit (Bardeen, Press & Teukolsky 1972). However, it is not yet completely clear that the inner disc radius inferred from observations (e.g. via iron line diagnostics) completely determines the black hole spin (e.g. Agol & Krolik 2000; Krolik & Hawley 2002). This is because, if emission from the plunging region between the marginal stable orbit and the event horizon is considered, even a moderate value of the black hole spin can reasonably well reproduce the results that would be obtained neglecting the plunging region emission and assuming a rapidly rotating Kerr black hole (Reynolds & Begelman 1997).

In this work we do not consider emission from matter accreting in the plunging region at $r < r_{\rm ms}$. However, since we study the case of a Kerr black hole with a disc extending down to the marginal stable orbit,, the plunging region has a very limited radial extent ($\Delta r = r_{\rm ms} - r_{\rm hor} \simeq 0.18\ r_g$) so that the contribution of these photons should be small. In fact, even in the most extreme case we are considering here (a very low source height of $h_s = 1\ r_g$), the fraction of photons that illuminate the plunging region is found to be negligible (less than 0.1 per cent of emitted photons).

As mentioned, the situation would be different in the case of a non–rotating black hole in which case the plunging region radial extent is $\Delta r = 4\ r_g$ and might contribute to the disc emission, producing results that would resemble those obtained in the maximally rotating Kerr case (see e.g. Reynolds & Begelman 1997; Young, Ross & Fabian 1998). The analysis of the non–maximally rotating case, with the inclusion of the plunging region emission, is potentially very interesting, but beyond the scope of this paper which, for simplicity, is restricted to the Kerr case.

The primary emission is due to a ring–like primary source of hard X–rays that emits isotropically in its rest frame with a luminosity described by a power–law. The primary source is located above the accretion disc at a distance ρ_s from the black hole axis and at height h_s above the equatorial plane. In this work, we restrict our analysis to a centrally concentrated source with $\rho_s = 2\ r_g$ and height between 1 and 20 r_g. However, similar results are obtained if the distance from the axis is kept within $\rho_s \approx 4\ r_g$, while the effects we shall discuss are reduced if ρ_s is larger. We also present some results for the case of a source on the rotation axis, previously extensively studied by e.g Martocchia, Karas & Matt (2000). It is not our purpose here to explore the full parameter space of possible source positions. Our results are expected to be qualitatively applicable in all the cases were a centrally concentrated primary source of X–rays can be inferred from the data (e.g. from the presence of a steep emissivity profile on the disc, a broad iron emission line and/or an inner disc reflection component).

The source could be physically realised by X–ray emission originating above the very inner regions of the disc and related to magnetic dissipation. In this case, dissipation of the black hole (or accreting matter) rotational energy represents one possible physical energy reservoir (Blandford & Znajek 1977; Agol & Krolik 2000; Li 2003); the role of a non–zero black hole spin is likely to be relevant and, in any case, dissipation is expected to be concentrated in the very inner regions of the accretion flow (de Villiers, Hawley & Krolik 2003; Hirose et al. 2003). The primary source could also be associated with the inner part of an aborted jet producing relativistic particles illuminating the disc (Malzac et al. 1998; Petrucci et al. in preparation) or to the aborted jet itself (Ghisellini, Haardt & Matt 2003). Another possible realisation could be self-Compton emission from the base of a weak jet (see e.g. Markoff, Falcke & Fender 2001). Any other mechanism producing a compact emission region above the innermost part of the accretion flow would be compatible with our model; this kind of geometry (often with a point–like source) has been previously adopted in a number of works (Martocchia & Matt 1996;

Henri & Petrucci 1997; Petrucci & Henry 1997; Reynolds et al. 1998; Bao, Wiita & Hadrava 1998; Lu & Yu 2001; Goyder & Lasenby 2003). Since in many reasonable cases a strong link between the accretion disc and the primary source is likely (e.g. via magnetic fields), we assume that the source is corotating with the same orbital velocity as the underlying disc (Ruszkowski 2000).

The orbital motion of the primary source justifies our choice of a ring–like geometry for the emitting region instead of the more commonly used point–like configuration: assuming for a moment that the (corotating) primary source is point–like, the temporal resolution of present observations (at least a few ks are needed to extract meaningful spectra) is longer than the orbital timescale close to the central supermassive black hole. Thus, our current instruments can only detect spectral features from many orbital revolutions, so that any information on the azimuthal position of the corotating point–like source is lost in the data. In comparing theoretical models with present observations, the primary source is then best described by assuming a ring–like geometry. Moreover, we cannot exclude that the primary source is itself axisymmetric and has a real physical ring–like configuration if the associated physical mechanism (e.g. magnetic reconnection, hole rotational energy extraction, link with a jet–like structure ...) had such a symmetry.

A fraction of the radiation emitted by the primary source directly reaches the observer at infinity and constitutes the direct continuum which is observed as the power–law component (PLC) of the spectrum. The remaining radiation illuminates the accretion disc (or is lost into the hole event horizon). The radiation that illuminates the disc is reprocessed into iron fluorescent photons produced at 6.4 keV by cold, non–ionised matter according to the work by George & Fabian (1991). In this work, we do not solve the radiation transfer within the disc nor consider the effects of ionisation of the disc surface so that the reflection continuum and possible shifts in the line rest–frame energy are neglected.

Hereafter, the (neutral) iron line emission will represent the whole reflection–dominated component (RDC) of the spectrum. We are of course aware that a precise definition of the RDC should include the reflection continuum and not only the iron line. However, in this work we are mainly interested in the variability properties and correlations of the direct continuum (the PLC) and the reflection components from the accretion disc and not in the detailed spectral shape of these components. Since iron line emission and (disc) reflection continuum are different aspects of the same physical phenomenon (reprocessing of the illuminating flux), it is expected that they vary together (and they must, within our model). Thus, we believe that, as far as variability and correlation properties are concerned, the study of the iron line provides an excellent approximation to the variability of all the other components that are produced by reprocessing of the illuminating continuum in the accretion disc, i.e. the whole RDC.

We do not exclude that ionisation of the disc surface can contribute to the RDC variability (Ross, Fabian & Young 1999; Nayakshin, Kazanas & Kallman 2000; Nayakshin & Kallman 2001; Collin et al. 2003). However, as we shall discuss, many of the observed variability can be explained even without invoking ionisation effects once special and general relativity are properly taken into account.

2.2 X–ray variability induced by gravitational light bending

As already mentioned in the introduction, the variability of the iron line (and of the RDC) in some sources is found to be uncorrelated with the continuum, challenging theoretical models of reflection from accretion discs. In the standard picture of reflection models, roughly half of the photons emitted from the primary source reaches the observer at infinity as direct continuum (or PLC), while the remaining half illuminates the accretion disc, is reprocessed and reaches the observer at infinity as the RDC of the spectrum. The X–ray variability is assumed to be mainly due to intrinsic luminosity variability of the primary source; the luminosity variation affects in the same way both the direct continuum and the illuminating flux on the accretion disc so that any RDC, including the iron line, has to respond to the PLC variation. In this framework, a constant iron line equivalent width and a constant value of the reflection fraction would be produced, in contrast with many observations.

Here we adopt a different point of view with the aim of reconciling the observed variability properties with theoretical models of disc reflection. In this work, we assume that the intrinsic luminosity of the primary source is constant and that the observed variability is induced by gravitational light bending of the primary photons emitted by the source. The basic idea is that the relevant parameter for the variability of both the PLC and the illuminating continuum on the disc (which drives the RDC variability) is the height of the primary source above the accretion disc. The main difference with respect to the standard picture is that changes in the height of the primary source affect in different ways the direct and the illuminating continua so that the RDC is not anymore expected to be strictly positively correlated with the PLC.

As an example, if the source height is small (of the order of few gravitational radii) a large fraction of the emitted photons is bent towards the disc by the strong gravitational field of the central black hole enhancing the illuminating continuum and strongly reducing the PLC at infinity, so that the spectrum is expected to be reflection–dominated. If the source height increases, the gravitational potential that photons have to overcome to reach infinity is reduced, so that more photons reach infinity and the observed PLC increases; in the same time, the illuminating continuum on the disc is, in general, reduced (but depends also on the fraction of photons that are lost into the black hole event horizon). Finally, if the height is very large so that light bending is not very effective, the standard picture of reflection models with approximately half of the emitted photons being intercepted by the disc and the remaining half reaching the observer as the PLC is recovered.

It is clear that reflection responds to variations in the illuminating continuum but not necessarily (or not in an intuitive way) to changes in the direct, observed continuum that reaches the observer at infinity as the PLC. The illuminating continuum is the radiation emitted from the primary source *as it is seen from an observer on the accretion disc*, while the direct continuum (or PLC) is the same radiation but *as it is seen from an observer at infinity*. The very different location (and thus the very different gravitational field) and state of motion of the two observers make all the difference between the illuminating and direct continuum. The RDC that we detect at infinity and its correlation properties with the PLC have then to be computed from the illuminating continuum in a general relativistic framework that takes into account all the effects on photon propagation in the strong gravitational field of the central (Kerr, in the present work) black hole.

It is also clear that our assumption that the intrinsic luminosity of the source is constant is a simplification. In the general case, we expect that the variability is due to both intrinsic variations and light bending effects. However, the purpose of this work is to present the model and to show that light bending, even alone, can reproduce

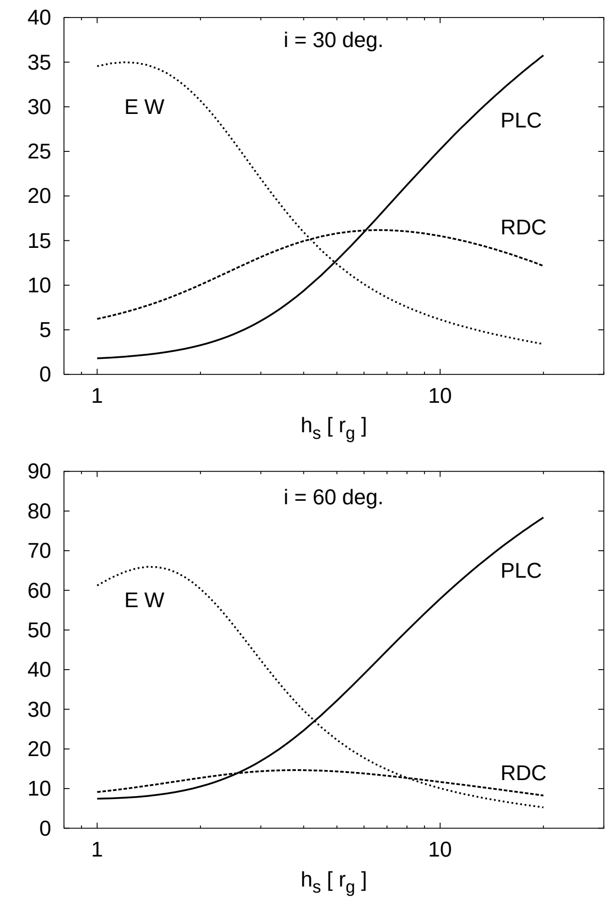

Figure 1. The iron line equivalent width (EW), the reflection–dominated component (RDC, represented by the iron line) and the direct continuum flux (PLC) as a function of the height h_s of the primary source above the equatorial plane. The variations in the continuum and line flux are obtained by varying the source height from 1 to 20 r_g at fixed intrinsic luminosity. The variability is then induced by light bending alone. The source is located at a distance of 2 r_g from a Kerr black hole rotation axis and it is represented by a ring–like source corotating with the accretion flow. The top panel refers to an observer inclination of 30 degrees while the bottom panel is for an inclination of 60 degrees. Units are arbitrary.

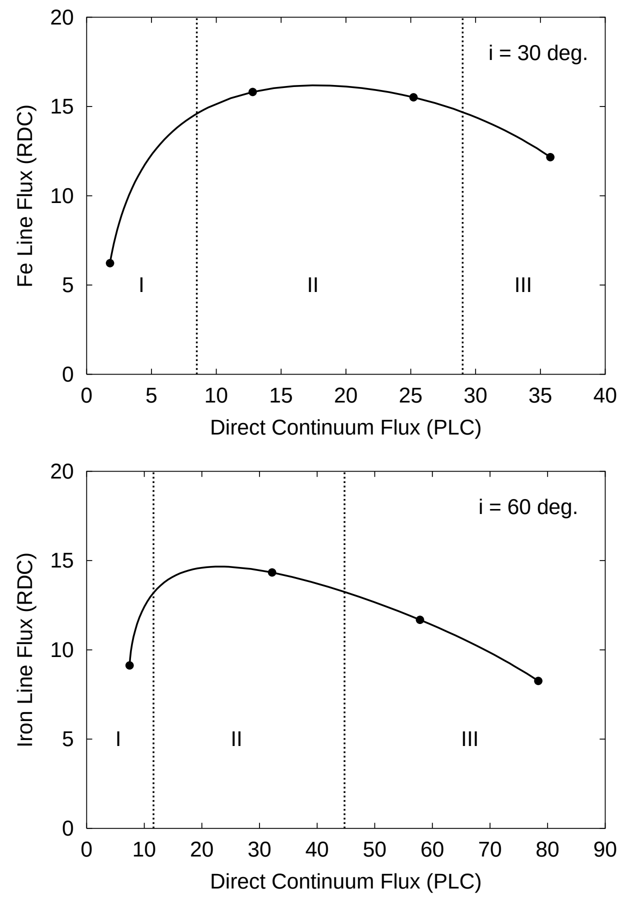

Figure 2. The iron line flux (RDC) as a function of the direct continuum flux (PLC) for an observer inclination of 30 (top panel) and 60 (bottom panel) degrees. The source configuration is the same as in Fig. 1 and its height varies between 1 and 20 r_g. As a reference, black dots indicate different values of the source height: from left to right these are $h_s = 1\ ,\ 5\ ,\ 10\ ,\ 20\ r_g$. Three different regimes are identified (I, II and III, see text for details). Units are arbitrary.

many of the observed spectral variability properties of some X–ray sources.

3 PREDICTIONS OF THE LIGHT BENDING MODEL

In Fig. 1, we show the RDC (represented by the iron line) and PLC fluxes and the iron line equivalent width (EW) as a function of the height h_s of the primary X–ray source for a corotating ring–like source with $\rho_s = 2\ r_g$ and $1 \leqslant h_s \leqslant 20\ r_g$. The two panels refer to two different observer inclinations (30 and 60 degrees). The luminosity of the primary source is assumed to be constant so that the PLC and RDC variability is produced by light bending alone. As shown in Fig. 1, the PLC is strongly correlated with the source height so that low flux states (low PLC) are associated with low source heights and vice–versa. As the source height changes, large variation of the PLC are allowed while the RDC varies with much smaller amplitude. As an example, for an observer inclination of 30 degrees, the maximum variation induced by a change of the source height from 1 to 20 r_g is about a factor 20 for the PLC, while the iron line (and the RDC) varies at most by a factor 2.6. At 60 degrees, one has a variation by a factor 10.5 for the PLC and only 1.8 for the reflection component.

The iron line EW is almost always anti–correlated with h_s (i.e. with the direct continuum, or PLC, see Fig. 1). However, the EW can be almost constant during extremely low flux states when the source height is very low (see Fig. 1). As already mentioned, one of the limitations of the present work is that we do not solve the radiation transfer within the disc, so that we neglect the reflection continuum. Although this does not affect much the analysis of the RDC variability (because the reflection continuum has to vary in the same way as the iron line), the value of the iron line EW is affected. Our results refer to the EW computed with respect to the power–law continuum only, do not include the reflection continuum, and can be tested against data if, during data analysis, the same procedure to compute the line EW is adopted (see e.g. Miniutti, Fabian & Miller 2003). The main effect of the reflection continuum is expected to be a saturation of the line EW in those situations where reflection dominates the spectrum, i.e. when the source height is low (see e.g Ross & Fabian 1993; Ballantyne & Ross 2002). Thus, a more realistic picture for the EW behaviour is the one in which an asymptotic constant value is reached as the

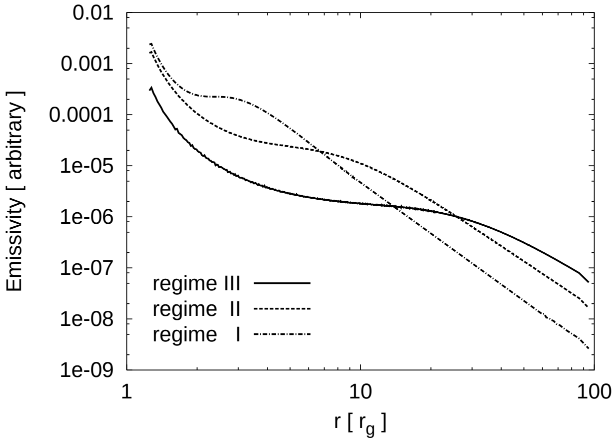

Figure 3. We show the typical emissivity profiles on the accretion disc during regimes I, II, and III for the same source configuration as in the previous Figures. As a general rule, the emissivity is steeper in the inner regions of the disc and flatter in the outer. Moreover, the overall shape is steeper going from regime III (high source height and high PLC flux) to regime I (low source height and low PLC flux) because, as the source height is lower, the inner regions of the disc are more illuminated than the outer.

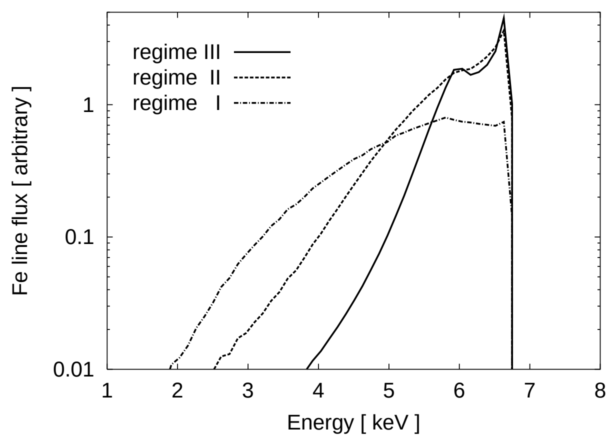

Figure 4. We show the typical iron line profiles during regimes I, II, and III with the same primary source configuration as in the previous Figures, for an observer inclination of 30 degrees. A logarithmic scale is used in the y–axis to help to visualise the differences. The line is broader and fainter during regime I (low PLC flux states), reaches its maximum flux during regime II (intermediate PLC flux states) and becomes narrower and slightly fainter again during regime III (high PLC flux states), mainly because the red wing is reduced. As shown in Miniutti et al. (2003), the iron line profile of regime II provides a reasonably good description of the iron line of MCG–6-30-15 in the long *XMM–Newton* observation by Fabian et al. (2002a).

source height decreases. We shall discuss again this effect later in this Section.

The relationship between the iron line flux (or RDC) and the direct continuum that we observe (or PLC) is illustrated in Fig. 2. We show the iron line flux as a function of the observed direct continuum for an inclination of 30 degrees (top panel) and 60 degrees (bottom panel). The plot of the RDC flux versus the direct continuum shown in Fig. 2 allows to identify three regimes in which the behaviour is clearly different (regimes I, II and III, corresponding to labels in Fig. 2). The typical emissivities on the disc and typical iron line profiles obtained in the three different regimes are shown in Fig. 3 and 4. The following discussion defines the regimes, illustrate their properties and refers to Figures 1-4, where the same primary source configuration has been used.

(i) *Regime I*: in this regime the observed direct continuum is very low. Regime I corresponds to a low height of the primary source, where the strong light bending suffered by the primary radiation dramatically reduces the observed PLC at infinity (see Fig. 1 and 2). The iron line flux and the direct continuum are positively correlated. Since the flux illuminating the disc is concentrated in the inner regions, a steep emissivity profile and a broad and redshifted iron line are produced, as shown in Fig. 3 and 4. The iron line equivalent width is almost constant at very low heights and starts to decrease as the transition to regime II is approached. Because the RDC varies less than the PLC, the spectrum is more and more reflection–dominated as the source height and the direct flux are lower (see also Section 3.1). The effect of the reflection continuum, that we neglected in this work, would be to produce an even more constant line EW in this regime. This is because, as the spectrum becomes reflection–dominated, the line and the continuum (almost only reflection) vary together so that the line EW remains constant reaching an asymptotic value. We must then expect an almost constant line EW during regime I, corresponding to a low PLC flux and to a reflection–dominated spectrum. Regime I is associated with $h_s \lesssim 2 - 4 r_g$, depending on the observer inclination.

(ii) *Regime II*: we identify this regime by requiring that the iron line flux varies less than 10 per cent around its peak value. In other words, the iron line (and any RDC) has basically constant flux while the direct continuum (PLC) can vary by a factor $\sim$ 3–4 (see Fig. 2). The line EW is anti-correlated with the PLC (see Fig. 1) and changes in the line profile with flux are subtle and difficult to detect. We do not expect a large effect on the line EW caused by the reflection continuum in this regime, so that the anti–correlation will be maintained. Regime II was studied in more detail in Miniutti et al. (2003) and accounts for the variability of about a factor 4 in the PLC together with an almost constant iron line as revealed by *ASCA* and *XMM-Newton* long observations of MCG–6-30-15 (Shih, Iwasawa & Fabian 2002; Fabian & Vaughan 2003). During this regime, the RDC reaches a maximum. Regime II corresponds to $2 - 4r_g \lesssim h_s \lesssim 7 - 13r_g$, depending on the inclination.

(iii) *Regime III*: in this regime light bending is less effective (but still present) and the observed direct continuum at infinity can be large. In regime III, the iron line flux is anti–correlated with the PLC and the line EW continues to decrease with the PLC, as in regime II. The line profile is much narrower than in regimes I and II because the emissivity profile on the disc is flatter, as a result of nearly isotropic illumination (see Fig. 3 and 4). When the source height is very large (say $h_s \geqslant 30\ r_g$, not shown in the Figures) and light bending does not affect the emission anymore, both the line and the direct continuum (and, of course, the EW) tend to their asymptotic values.

These results are in good agreement with the analysis of the long–term variability of a selection of AGN based on data from the *Rossi X–ray Timing Explorer (RXTE)* as reported by Papadakis et al. (2002). The authors found a general anti–correlation between the iron line EW and the continuum flux. The light bending model predicts that the EW is most of the time anti–correlated with the continuum, as shown in Fig. 1. The only exceptions are during low flux states of regime I or extremely high flux states of a deep regime III where an almost constant EW can be produced. Moreover, the EW of the iron line is not necessarily correlated with the reflection–dominated component flux. This is especially true in regime I (al-

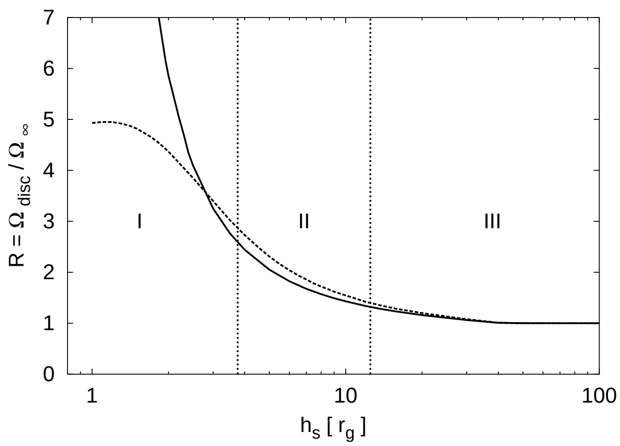

Figure 5. The reflection fraction R as a function of the height of the primary source above the equatorial plane. The asymptotic value (R=1 and $\Omega_{\rm disc} = \Omega_\infty = 2\pi$) corresponds to half of the primary source radiation reaching the disc and half infinity. The cases of a source on the rotation axis (solid) and of a corotating source at $2r_g$ from the axis (dashed) are shown. We also show the three different regimes defined for an inclination of 30 degrees (appropriate for MCG–6-30-15 and NGC 4051). The variation of R with h_s is due to light bending alone.

most constant EW while the RDC increases with the continuum) and regime II (decreasing EW and almost constant RDC). Only regime III is characterised by a clear positive correlation between the EW and the RDC (both anti–correlated with the continuum for h_s smaller than about 30 r_g).

We point out again that, considering the three regimes altogether, the iron line (and RDC) varies with much smaller amplitude than the PLC. This behaviour is also observationally confirmed by the long–term variability of seven Seyfert 1 galaxies studied in detail by Markowitz, Edelson & Vaughan (2003).

As mentioned, it is also possible (and very likely) that intrinsic luminosity variations of the primary source are superimposed on those due to height changes and that they exist both on short and long timescales. This will lead to correlated variability between the PLC and the RDC that may be most observable when the source height undergoes a period of relative constancy (or, of course, when light bending is negligible, say $h_s \geqslant 30\ r_g$).

3.1 Low–flux states and reflection–dominated spectra

As the source height decreases, our model predicts that the spectrum becomes more and more reflection–dominated because light bending reduces the observed PLC flux and tends to enhance the illumination of the disc and thus the RDC. The reflection fraction is thus expected to be large as a low flux state is reached. Here we define the reflection fraction to be $R \equiv \Omega_{\rm disc}/\Omega_\infty$ i.e. the ratio between the solid angle subtended by the primary source at the disc ($\Omega_{\rm disc}$) and at infinity (Ω_∞).

In Fig. 5 we plot the reflection fraction as a function of the height above the disc for a source on the rotation axis of a maximally rotating Kerr black hole and for a corotating source at $2r_g$ from the rotation axis. We also show, as a reference, the three different regimes defined above for an observer inclination of 30 degrees, which is appropriate for the cases of MCG–6-30-15 and NGC 4051 that we shall discuss in detail later.

The maximum reflection fraction is about 5 for the off-axis source, and tends to unity for large heights, where light bending effects are negligible. Notice that the overall normalisation of R can vary from source to source: here we assume that when light bending is negligible (large h_s) half of the primary continuum illuminates the disc, the remaining half reaching infinity. For the on–axis case, we restrict our plot in Fig. 5 to $R \leqslant 7$; if the height is lower than about 2 r_g, as the source approaches the black hole event horizon only a tiny fraction of the emitted photons are able to reach infinity (Dabrowski & Lasenby 2001; Martocchia, Matt & Karas 2002; Miniutti et al. 2003) and the reflection fraction can be much larger. As an example, if the source is on–axis and $h_s = 1.25\ r_g$, only about 1.2 per cent of the emitted photons reach infinity, 21.9 per cent hit the disc (and are reprocessed as the RDC) and 76.9 per cent are lost into the hole, so that the spectrum would be interpreted as if the primary source had switched off, leaving only a reflection–dominated component with $R \approx 18$.

The anisotropy ratio $\Omega_{\rm disc}/2\pi$ can be obtained from R by considering that $\Omega_\infty \equiv 4\pi - (\,\Omega_{\rm disc} + \Omega_{\rm hole}\,) \approx 4\pi - \Omega_{\rm disc}$, where $\Omega_{\rm hole}$ is associated to photons that are lost into the black hole event horizon. This is only a very crude upper limit, as $\Omega_{\rm hole}$ should not be neglected, especially in the case of low source height. However, since the anisotropy ratio is sometimes used instead of R in both observational and theoretical works, we give, as an example, the approximate conversion $\Omega_{\rm disc}/2\pi \lesssim 2\,R/(\,1+R\,)$ (see also Martocchia, Matt & Karas 2002).

3.2 Beaming in the equatorial plane

There is another general/special relativistic effect that can produce additional reflection spectral signatures. Due to gravitational lensing and special relativistic beaming, the emission from the inner regions of the disc is significantly beamed along the equatorial plane (Cunningham 1975). Applications of relativistic beaming in the hole equatorial plane have also been previously considered as a possible explanation for the unusual extreme variability of IRAS 13224–3809 as well as for its strong soft excess (Sun & Malkan 1989; Boller et al. 1997).

Observing equatorial beaming

The beaming in the equatorial plane of a Kerr black hole is illustrated in Fig. 6 where a polar diagram of the number of photons (per unit area) that reach infinity being emitted from three different rings in the equatorial plane ($\equiv$ accretion disc) is shown. It is clear that the emission from the disc is far from isotropic, especially if the emitting region is close to the black hole resulting in a much larger number of photons detected at 90 degrees than at 0 degrees (see also Dabrowski et al. 1997 for a similar figure). This effect is more pronounced for inner emitting rings, as shown in Fig. 6. Thus, beaming along the equatorial plane is more effective when the disc emissivity is centrally concentrated, i.e. in low flux states (e.g. a regime I, see Fig. 3).

The beaming of the emission along the equatorial plane is maximal when the emitting region lies in the inner equatorial plane of the black hole (i.e. radiation emitted/reflected from the inner regions of the accretion disc). However, the same effect arises also if the source has a finite height above the disc (i.e. continuum radiation emitted from the primary X–ray source). If the primary continuum originates at low heights, even this radiation is preferentially emitted along the equatorial plane, although the beaming is reduced as the height increases. Thus, during low flux states both the primary continuum and the disc emission are preferentially emitted

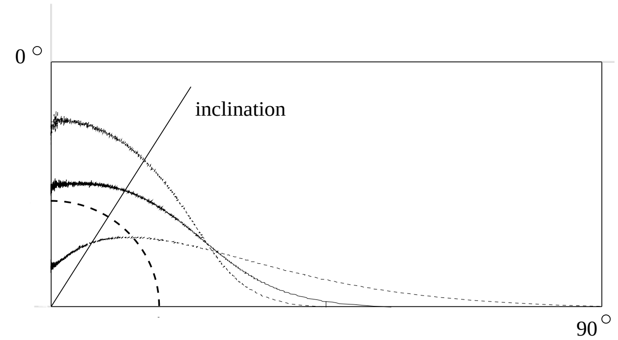

Figure 6. Polar diagram showing the number of photons per unit area that reach the observer at different inclinations. Photons are emitted by annuli in the equatorial plane of a Kerr black hole (the accretion disc). Looking at the left side of the plot, the emission radii (r_s) are 2, 4 and 8 r_g from bottom to top. The dashed circle represents, as a reference, the case of isotropic emission. The intercepts of the lines with the y–axis is the number of photons (per unit area) detected at 0 degrees, while the intercept with the x–axis is the number of photons detected at 90 degrees. It is clear that photons are preferentially emitted along the equatorial plane so that the number of photons detected at 90 degrees is larger than at 0 degrees, contrasting strongly with the isotropic case.

along the equatorial plane. In the following we describe some of the observable consequences of equatorial beaming:

(i) a distant reflector (torus) and/or a disc that slightly diverges from the equatorial plane will intercept most of the radiation that is emitted from the innermost regions of the disc. The net effect is that narrow reflection features could be present in the spectra, associated with reflection from distant matter. In general, one must expect larger narrow features in low flux states, when the emissivity on the disc is concentrated in the inner regions so that beaming along the equatorial plane is maximal (and some contribution from the beamed primary continuum is also expected). The narrow features, if present, will superimpose on the broad and redshifted ones that are produced in the inner disc making it difficult to distinguish between narrow and broad components, especially in short observations or faint sources;

(ii) the reflection spectrum produced by the inner disk surface has a strong soft X-ray/EUV component due to oxygen and lower Z elements being highly ionised, so making the albedo very high there, and to bremsstrahlung emission. Together with the intrinsic thermal UV radiation from within the disk, this is beamed along the plane of the disk as shown by Fig. 6. If the Balmer lines such as Hβ are then produced by EUV irradiation of clouds close in height to the disk (but at distances of thousands of gravitational radii) and the systems are observed at low/moderate inclination, then the observed line widths will be small. The anisotropic nature of the irradiation of the broad-line clouds in such systems may therefore help to make them appear narrow. Peterson et al (2000) have argued that the optical lines in NGC 4051 can be explained by the broad-line region (BLR) being flattened and viewed at low/moderate inclination. Our model causes the BLR to appear flattened due to the anisotropic irradiation;

(iii) in the standard unified model, Seyfert 2 galaxies are viewed at high inclination (Antonucci 1993). This means that those for which the black hole has a high spin (so that the disc extends close to the horizon) should have a strong reflection component in the transmitted radiation. If the X-ray absorption due to the surrounding torus and other gas is strong, such strong reflection may only be evident in the Compton reflection bump at about 30 keV;

(iv) the companion star in stellar mass, black hole X-ray binaries samples the equatorial radiation. If the inner disc radius is small and the binary observed at moderate to low inclination, the equivalent width of the iron line due to reflection on the star could then be greater than expected. This could be relevant to observations of Cyg X-1 (e.g. Miller et al 2002c). A contribution from the outer region of a flared disc could also increase the narrow line equivalent width;

(v) we also point out that, since several microquasars (e.g GRS 1915+105; Mirabel & Rodriguez 1999) are viewed at high inclination, the reflection spectrum could be very strong due to equatorial beaming, especially during low flux states.

From the discussion above, it appears that narrow features are expected to be larger during low flux states. A natural prediction of our model is that the EW of narrow lines from the outer regions of the disc, the torus, and/or the BLR should anti–correlate with the flux of the source. This prediction holds for single sources whose flux changes, but could have some relation with the observed X–ray Baldwin effect (anti–correlation between lines EW and luminosity, Baldwin 1977), first reported for narrow iron lines by Iwasawa & Taniguchi (1993) and then confirmed by Nandra et al. (1997) and Page et al. (2003).

3.3 Variability timescales

The model we are proposing must be able to produce the variability we observe in some X–ray sources without invoking extreme conditions. Light bending–induced variability is associated with changes in source height: if these changes are produced by different active regions appearing at different times and different heights, the induced variability will depend on the physical mechanism that activates the different emitting regions. On the other hand, if the height changes are produced by the motion of a single (or dominant) X–ray emitting region, the variability timescale is determined by the vertical velocity of the source. Notice that, in the latter case, more than one single timescale is expected, e.g. a shorter one due to small–scale height fluctuations, and a longer due to large–scale source motion.

A variability by a factor 20 in the observed flux can be obtained for an inclination of 30 degrees if the source height changes from 1 to 20 r_g. For a 10^7 $M_\odot$ black hole, this variability can be produced in less than 2 ks by a single primary source even if the motion is not highly relativistic (say 0.05 c). With the same setup, the shortest possible doubling time would be less than 200 seconds.

We must point out that the most extreme variability in the *XMM–Newton* observation of MCG–6-30-15 by Fabian et al. (2002a) is a factor 4 in about 10 ks, well within the limits of the the light bending model and allowing a single source as slow as $\approx$ 2.5×10^{-2} c. Some Narrow Line Seyfert 1 galaxies and other sources show remarkably fast and large flux variations (Boller et al. 1997; Remillard et al. 1991) which appear in some cases to exceed the “efficiency limit” (Fabian 1979; Brandt et al. 1999) with doubling times of few hundreds of seconds. These variations could however be a consequence of the light bending effects discussed here and need not to be intrinsic to the primary continuum.

In their analysis of the long–term variability of a sample of Seyfert 1 galaxies, Markowitz, Edelson & Vaughan (2003) found (besides the weaker variability of the iron line with respect to the continuum) that the iron line, like the continuum, exhibits stronger variability towards longer timescales. It is not our purpose to explain this behaviour here, but merely note that if the variability is

produced by the (vertical) motion of a single primary X–ray source, we expect, in general, that the strongest variability in both PLC and RDC will be seen on longer rather than shorter timescales. Variability on short timescales could be due to small fluctuations in the source height (producing weak variability of the PLC and RDC), while on longer timescales the primary source might cover large distances producing larger variations in both components (see e.g. Fig. 1).

In the case of a stellar–mass black hole, strong variability in the PLC can be produced in a much shorter timescale than in AGN because the distance that the (single) primary source must travel scales with the black hole mass. Assuming, as before, a velocity of the primary source of $0.05\ c$, the PLC can vary by a factor 20 in a timescale 10^6 times shorter for a $10\ M_\odot$ black hole than for a typical AGN with $10^7\ M_\odot$, i.e. such variation can be reached in few milliseconds (again for an observer inclination of 30 degrees).

Even more dramatic variations are produced for a more face–on inclination and, clearly, if the primary source is moving more relativistically. As already mentioned, the variability may also be associated with the appearance of different active regions at different heights. In this case, no source motion is implied and large variations may be seen, in principle, on arbitrarily short timescales.

4 SOME APPLICATIONS TO AGN

In this Section, we discuss the phenomenology of the Seyfert galaxies MCG–6-30-15, NGC 4051 and other Narrow Line Seyfert galaxies and we compare the observational results with the predictions of our light bending model.

4.1 MCG–6-30-15

The spectrum and variability of the Seyfert 1 galaxy MCG–6-30-15 in its normal flux states can be accounted for by a phenomenological two–component model consisting of a variable power law representing the direct continuum and an almost constant reflection–dominated component which contains the broad iron emission line (McHardy, Papadakis & Uttley 1998; Shih, Iwasawa & Fabian 2002). This model is also supported by the analysis of the correlation between fluxes in different energy ranges using both *RXTE* data (Taylor, Uttley & McHardy 2003) and *XMM–Newton* observations (Vaughan & Fabian 2003). The analysis reveals the existence of a soft component varying in normalisation and an additional almost constant harder spectral component. The interpretation of these components as the PLC and the RDC is natural. The two–component model explains also the rms spectrum of the source and the correlation between spectral slope and flux. A detailed discussion of the long 2001 *XMM–Newton* observation by Fabian et al. (2002a) that is representative of the normal flux state of MCG–6-30-15 is made by Vaughan & Fabian (2003).

The lack of correlation between the two main spectral components represents a challenge for the standard picture of reflection models because, as already stressed, any reflection feature should respond to the variations in the continuum, especially if it is produced in the inner regions of the accretion disc as the reflection spectrum of MCG–6-30-15 (and most remarkably the iron line shape) indicates. However, as pointed out by Fabian & Vaughan (2003), the two–component model for the variability of this source could be perhaps explained self–consistently by taking into account light bending effects in the near vicinity of the black hole.

This suggestion was explored in detail by Miniutti et al. (2003) where the application of the light bending model to the case of MCG–6-30-15 was presented for the first time. The relationship between the RDC and the PLC shown in Fig. 2 demonstrate how an almost constant RDC (and iron line) is obtained during regime II despite a variation of the PLC by a factor ~ 4, in agreement with the observations by Shih, Iwasawa & Fabian (2002), Fabian & Vaughan (2003) and with the discussion presented in Vaughan & Fabian (2003).

Notice that during the 2001 observation, the line (and RDC) is indeed likely to vary within 25 per cent (with respect to a continuum variation of about a factor 4). Thus, this observation could be described by including a contribution from a regime I, in which the line is slightly more variable than in a pure regime II. The regime I contribution would be associated with the lowest flux epochs of the observation.

The iron line profile obtained from our model if the primary source height is confined within about 8 r_g provides an adequate fit to the 2001 *XMM–Newton* observation, supporting our interpretation (Miniutti et al. 2003). The emissivity profile is observationally best described as a broken power law, steeper in the inner disc than in the outer, in agreement with the light bending model predictions (see Fig. 3). The iron line EW is observationally found to be anti–correlated with the continuum during this same 2001 *XMM-Newton* observation (Vaughan & Fabian 2003) and this is the behaviour we found for the EW during regime II (see Fig. 1). Furthermore, the observed reflection fraction ($R \gtrsim 1.4$ in the *XMM–Newton* data and $R \approx 2$ in the simultaneous high energy *BeppoSAX* data) is also consistent with regime II, as shown in Fig. 5.

Summarising, the Seyfert galaxy MCG–6-30-15 in its normal flux state, represented here by the long 2001 *XMM–Newton* observation, exhibits an almost constant iron line and RDC, a PLC varying by about a factor 4 and an iron line EW which is anti–correlated with the continuum. All these observational properties, together with the iron line profile and the relative strength of disc reflection, can be reproduced by considering the source in regime II (with a possible contribution from regime I during the lowest flux epochs).

As already discussed in Miniutti et al. (2003), the light bending model predicts some changes in the profile of the iron line at different flux states. The line will appear narrower when the PLC flux is high and broader when dim; differences which are subtle and difficult to detect in observations during a normal state of the source (i.e. a regime II according to our interpretation). However, if the PLC had a significantly lower (higher) flux, a broadening (narrowing) of the iron line should be detectable (see Fig. 4).

These predictions fit very well with the observations of MCG–6-30-15 in the so–called "Deep Minimum" state of the source identified by *ASCA* in 1994 (Iwasawa et al. 1996) and observed again in 2000 with *XMM–Newton* (Wilms et al. 2001) where a very broad iron line was detected. We point out also that during the 2000 "Deep Minimum" the reflection fraction is poorly constrained by the data and could be larger than 2.5, supporting the idea that the spectrum may become reflection–dominated in the very dim states (see Fig. 5). Large values of the reflection fraction can be inferred from the *ASCA* 1994 "Deep Minimum" observation as well. Furthermore, the iron line profile in this low flux state is very well reproduced by assuming an illuminating source on the rotation axis at $h_s = 3r_g$ (Martocchia, Matt & Karas 2002). Notice also that evidence for a narrower iron line when the source flux is high has been reported (Iwasawa et al. 1996; Lee et al. 2002) in agreement with the predictions of the light bending model. In particular, Iwasawa et al.

(1996), showed how the Fe line profile is dominated by the narrow component during a long bright flare, while, during the “Deep Minimum”, the broad red wing completely dominates: these observed profile changes match very well our predictions.

The 2000 “Deep Minimum” state of MCG–6-30-15 has been recently analysed in detail (Reynolds et al. 2003). One of the most interesting results is that the behaviour of the iron line with respect to the continuum appears to be different from that of the normal state of the source; in the low flux state, the iron line is found to be positively correlated with the continuum producing an almost constant line EW within a variation of about a factor 2 of the continuum. These results, together with the increase of the reflection fraction in low flux states of MCG–6-30-15, strongly suggest that the “Deep Minimum” state is best described by a regime I where the iron line is broader and correlated with the PLC (see Fig. 2) and the reflection fraction larger than in regime II. A deep regime I is also characterised by an almost constant line EW (see Fig. 1 and the associated discussion on the role of the reflection continuum during regime I), so that even this observational result is recovered.

By comparing the observational results on MCG–6-30-15 during its normal and low flux states with the theoretical predictions of the light bending model, it then appears that the main spectral and temporal properties of the broad iron line can be recovered by interpreting the normal flux state as regime II and the low flux (or “Deep Minimum”) state as regime I and by considering the variability to be mainly due to changes in the height of the primary X–ray source above the disc. The behaviour of the the iron line flux and EW with respect to the continuum match very well our predictions. Moreover, the iron line profile changes are also in agreement with our computations and the fact that the overall spectrum appears to be more and more reflection–dominated as the source flux decreases, further supports one of the main predictions of the light bending model.

4.2 NGC 4051

The Narrow Line Seyfert 1 galaxy NGC 4051 is a low luminosity AGN that exhibits long timescale flux changes. The source was observed in an extremely dim state in 1998 simultaneously by *Beppo*SAX and RXTE (Guainazzi et al. 1998; Uttley et al. 1999). The 1998 observations were interpreted by assuming that the active nucleus had switched off, leaving a reflection–dominated spectrum from distant material. The reflection spectrum is indeed consistent with reflection of a primary continuum with much higher flux than that seen. The straightforward explanation is that the reflector lies at large distances from the continuum source (more than 150 light days from the inspection of the light curve on long time scales, see Uttley et al. 1999) and keeps track of the continuum emitted before the central source switched off.

The study of the long–term variability of NGC 4051 can be a powerful tool for testing the model we are proposing. Lamer et al. (2003) reported on nearly 3 years of monitoring of NGC 4051 by *RXTE* (see also Uttley at al. 1998; 1999). These studies revealed that the primary source did not suddenly switch off in May 1998. The light curve evolution is more consistent with the source moving from a highly variable high flux state to the very low state of 1998 through an intermediate one. Furthermore, the long timescale variability is associated with the primary continuum itself and not e.g. to varying obscuration. These observations support the idea that the long timescale variability is dominated by changes in one underlying parameter (that may be the source height).

The variability analysis by Lamer et al. (2003) makes use of the idea that a constant reflection component from a distant reflector is always present and revealed by the 1998 ultra–dim state. The authors then subtracted this contribution in the analysis during the other, higher flux states. As a general rule, a positive correlation between the broad (i.e. emitted from the disc) iron line and the direct continuum is found, although epochs in which the line appears to be constant while the continuum varies by a factor ≈ 2 are also observed. If light bending is providing the most important mechanism for the observed variability, these behaviours would correspond to regime I and II respectively (see Fig. 2). The line equivalent width is found to be roughly constant or decreasing with the continuum, consistently with regime I where the EW is almost constant and regime II where it decreases with the continuum flux as shown in Fig. 1.

Recently, a *Chandra* observation of NGC 4051 during a 2001 low–flux state (not as low as the 1998 one) has been reported by Uttley et al. (2003a). Spectral curvature is present in the data and the hard residuals (with respect to a simple power law description of the continuum) cannot be explained in terms of reflection from distant material. Furthermore, the rapid broadband spectral variability is also inconsistent with this hypothesis. The presence of some distant reflector is not ruled out, but it does not contribute too significantly to the hard continuum spectrum. This result does not necessarily conflict with the interpretation of the 1998 spectrum because the 1998 continuum was fainter than the 2001 one and reflection from distant material could have been dominating.

As pointed out in Uttley et al. (2003a), a possible explanation of the hard spectral shape of the 2001 *Chandra* spectrum is that it is associated with strong reflection from the inner regions of the accretion disc. A good fit to the 3–10 keV data is obtained by considering strong disc reflection (with a reflection fraction of the order of 3 but not very well constrained) together with an associated iron line produced in the very inner regions of the accretion disc around a maximally rotating Kerr black hole. Results from a 2002 *XMM–Newton* observation during a similar flux state have been recently reported by Uttley et al. (2003b): a broad iron line is not formally required to describe the data (see also Pounds et al. 2003), although some amount of disc reflection is probably present together with reflection from distant material.

The 2001 and 2002 low state of NGC 4051, as observed by *Chandra* and *XMM–Newton* and the 1998 “ultra–dim” state, provide a possible test of the light bending model that was able to explain the variability of MCG–6-30-15 (Miniutti et al. 2003). In this model, the low states observed in NGC 4051 should correspond to a period during which the primary X–ray source was located at low heights above the disc (regime I according to the discussion in the previous Section). If this is the case, the observed spectrum becomes naturally reflection–dominated as most of the primary photons are bent onto the accretion disc enhancing the reflection features with respect to the primary continuum.

A reflection fraction of the order of that indicated in the analysis by Uttley et al. (2003a) of the 2001 *Chandra* data can be obtained if the primary source height is about $3\ r_g$, thus in a regime I (see Fig. 5). At these heights, the strong, redshifted, broad iron line invoked by Uttley et al. (2003a) as a possible explanation of the hard residuals is naturally produced. As already mentioned, a broad line is not formally required to describe the 2002 *XMM–Newton* data and the fainter 1998 *BeppoSAX* and *RXTE* observations, which seems to rule out the light bending model as a possible explanation of the variability in this source.

However, NGC 4051 might represent a case where light bending effects are extreme: the fact that NGC 4051 reached a state that

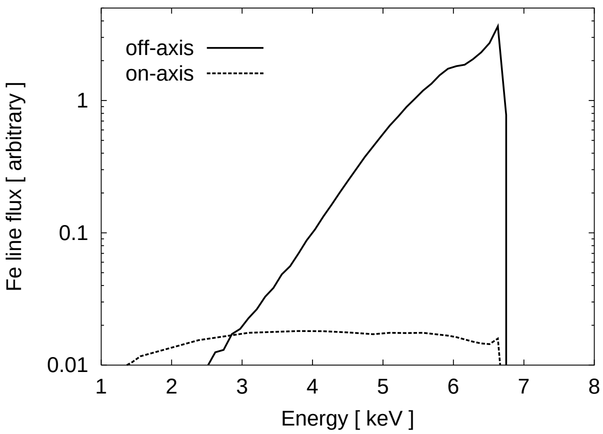

Figure 7. The iron line profiles for the cases of a primary source on the black hole rotation axis (on–axis) and $h_s = 1.7r_g$, and for a source at $\rho_s = 2r_g$ from the axis (off–axis) and $h_s = 6r_g$. Both line profiles are computed for an inclination of 30 degrees, appropriate for both MCG–6-30-15 and NGC 4051. The off–axis case is shown for comparison and is a typical profile for the regime II: this kind of profile fits well the MCG–6-30-15 data (see Fabian et al. 2002a; Miniutti et al. 2003) and is thus detectable with *XMM–Newton*. On the other hand, the detection of the line relative to the on-axis case would be much more challenging, if not impossible, once the line is "hidden" in the associated reflection continuum.

can be seen as if the primary source had switched off might suggest that the primary source is even more centrally concentrated than in MCG–6-30-15; indeed, if the source is low and on–axis, only a tiny fraction of the emitted photons can reach infinity because of the vicinity with the black hole event horizon, as discussed in Section 3.1. The spectrum is then completely dominated by reflection and the most straightforward interpretation would be that the source had switched off, as in the 1998 observations.

We point out here that, in this case, the iron line would be so broad that chances of detection would be seriously, if not totally, compromised. The line profile would be basically featureless, resulting in some spectral curvature below about 7 keV (depending on the ionisation and inclination) rather than in a clear emission–like feature. This is illustrated in Fig. 7 where we compare the iron line profiles obtained if an on–axis source at $h_s = 1.7\ r_g$ is considered, with a typical regime II line profile that was able to describe the 2001 *XMM–Newton* observation of MCG–6-30-15 and is thus detectable with this X–ray observatory: units are arbitrary but common between the two computations in order to allow direct comparison.

It is clear that the line resulting from the illumination by a very low–height on–axis source will be much more difficult, if not impossible, to detect against the associated disc reflection continuum (and the other components from distant material that are likely to be present in NGC 4051), possibly reconciling the light bending model even with the 1998 observations of NGC 4051 where no evidence for a broad line was reported (Guainazzi et al. 1998; Uttley et al. 1999). We do not show the line profile for a primary source at lower heights because it would be almost invisible in the Figure, even using the logarithmic scale. The fact that in the slightly higher flux states observed in 2001 with *Chandra* and 2002 with *XMM–Newton* the presence of the broad line is difficult to assess (Uttley et al. 2003a) or even not formally required (Uttley et al. 2003b), while disc reflection is probably present, might support our interpretation: if the height of the on-axis source is slightly larger than in Fig. 7, the resulting line profile would remain almost featureless but would have a slightly larger flux making possible, but difficult, its detection.

Thus we propose a possible scenario: the iron line would be detectable when it results in a relatively prominent emission–like feature during normal/high flux states of the source, while it would challenge detection in low states (source height around 3 r_g and reflection fraction R of about 3) and completely avoid observability in ultra–dim states ($h_s < 2\ r_g$ and larger R) because of its weakness and featureless spectral shape.

Furthermore, the 1998 spectrum of NGC 4051 was interpreted as dominated by reflection from distant material mainly because the measured average 2–10 keV flux is more than one order of magnitude lower than in any "normal state" while the iron line flux is only a factor 3 lower than in previous observations (see e.g. Guainazzi et al. 1996 and 1998). This interpretation seems the most natural and, as explained, is not necessarily in contrast with the 2001 and 2002 observations. However, this extreme difference in the continuum and line variations can be reached also by considering reflection from the inner regions of the disc plus light bending effects. Light bending alone can cause a large drop of the continuum flux as the source height goes to zero together with a much smaller line flux variation (see Fig. 2 and associated discussion). Moreover, the presence of an additional component from distant material can contribute to further confuse the picture.

We point out that the radial ionisation structure on the accretion disc, which we have neglected for simplicity, can play an important role especially during a deep regime I where one can reasonably expect the ionisation of the disc surface to be concentrated in the inner regions of the disc where the illumination flux is much larger (Matt, Fabian & Ross 1993; Matt, Fabian & Ross 1996; Ross & Fabian 1993; Ballantyne & Ross 2002). Ionisation and/or thermal instabilities (Nayakshin, Kazanas & Kallman 2000) could thus prevent or reduce the emission of the red wing of the iron line, possibly changing its correlation properties as well, and making even more difficult to detect the line in very low flux states (see also Uttley et al. 2003b for a discussion of this same possibility in the recently analysed 2002 *XMM–Newton* observation of NGC 4051).

4.3 Reflection–dominated spectra of NLS1 galaxies ?

Some Narrow Line Seyfert 1 galaxies (NLS1) show similar properties suggesting that their spectra may well be in some cases reflection–dominated, although this interpretation is not unique. Here, we focus on three sources, namely 1H 0707–495, IRAS 13224–3809 and IRAS 13349+2438.

1H 0707–495

1H 0707–495 was observed by *XMM–Newton* in 2000 October and the results of the spectral analysis reported by Boller et al. (2002). The most interesting result of this observation is the discovery a spectral feature around 7 keV where a sharp drop of more than a factor 2 in the spectrum has been detected. One possible explanation of such a drop is a partial–covering model provided by a patchy absorber (Holt et al. 1980). The spectrum can be modelled by a power–law with three absorbers resulting in a very good fit ($\chi^2_\nu = 177/178$).

Alternative explanations to the spectral shape of 1H 0707–495 have been proposed mainly by requiring the spectrum of the source to be reflection–dominated (Boller et al. 2002;

Fabian et al. 2002b). The drop at 7 keV may be seen as the blue wing of a strong, broad iron K_α line. A relativistically broadened line (with rest energy 6.4 keV and EW of about 5 keV) provides a good fit to the data if the emission comes from the inner regions of the disc around a maximally rotating Kerr black hole.

IRAS 13224–3809

IRAS 13224–3809 was observed with *XMM–Newton* on 2002 January 19 (Boller et al. 2003). As in the case of 1H 0707–495, a sharp and deep spectral drop was detected at about 8 keV. The observed spectral features can be explained in terms of absorption if, once again, a partial–covering model is invoked.

An alternative is again provided if one interprets the drop as the blue wing of a strong and relativistically broadened iron line produced in the accretion disc (seen at about 60 degrees) around a Kerr black hole (Boller et al. 2003); as in the case of 1H 0707–495, the required EW is large (larger than about 5 keV).

IRAS 13349+2438

IRAS 13349+2438 was observed by *XMM–Newton* on 2000 June 19 and 20 (Longinotti et al. 2003). A broad feature in the 5-7 keV region of the spectrum is observed, together with an absorption edge at about 7.4 keV. A partial–covering model with the associated transmission edge can describe the data but leaves residuals in the 5-7 keV band.

Another interpretation invokes reflection models which have the advantage to explain self–consistently the edge and the broad 5-7 keV feature. The best fit to the data is obtained with a phenomenological model comprising ionised reflection (the PEXRIV model from Magdziarz & Zdziarski 1995) coupled with a smeared edge and a diskline to account for the drop at 7.4 keV and for the broad 5-7 keV residuals, respectively. Even by adding the smeared edge component, the reflection fraction is found to be large (R around 2, depending on the continuum parametrisation).

A possible interpretation

We have seen that the spectra of some NLS1 galaxies can be interpreted as reflection–dominated with strong and broad iron line features, although different models such as partial–covering can describe the data equally well; only future, better data will allow, in our opinion, to discriminate between the different possible interpretations.

The light bending model can produce reflection–dominated spectra by simply varying one parameter (the primary source height) toward its extreme value ($h_s \to 0$) so that a transition into regime I is produced. These reflection–dominated spectra would be naturally associated with a strong iron emission line with different possible degrees of ionisation. Large values of the EW, such as those needed to interpret the drops at 7 and 8 keV in the spectra of 1H 0707–495 and IRAS 13224–3809 as the blue wing of a relativistic line, can in principle be reached if a certain degree of ionisation is allowed (Matt, Fabian & Ross 1993; Matt, Fabian & Ross 1996), as expected if the source height is low and illumination of the inner disc very strong.

We point out here that in order to produce a drop at 7–8 keV no extreme ionisation of the line is needed. Even a neutral 6.4 keV line can have a blue wing at 8 keV if seen at sufficiently high inclination. As an example, in Fig. 8 we show how neutral (i.e. 6.4 keV) iron lines are observed at inclinations of 30 and 60 degrees. It is clear from the Figure that the blue wing of an iron line seen at sufficiently high inclination can be located around 8 keV even if ionisation is not considered. Notice that a high inclination has sometimes been invoked to account for both the strong soft excess and the giant variability of this source (e.g. Boller et al. 1997). A higher line energy due to ionisation would allow a lower inclination of the system but is not formally required to explain the 8 keV drop of IRAS 13224–3809, while, as mentioned, ionisation could help to increase the line EW.

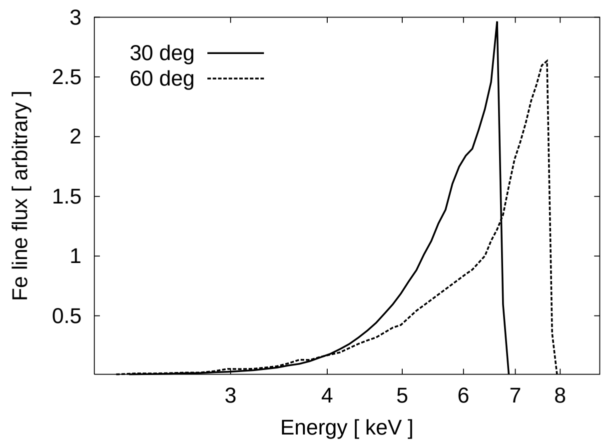

Figure 8. We show, as an example, the dependency of the iron line profile from the observer inclination. The line profiles are obtained with the same source configuration, have both a rest frame energy of 6.4 keV and only differ by observer inclination. The blue wing of a neutral, 6.4 keV line could in principle account for the spectral drop at 8 keV seen in IRAS 13224–3809 is seen at sufficiently high inclination. Larger inclinations would produce a blue wing at even higher energy than shown. A higher line energy (due to ionisation) would reduce the constraint on the inclination angle, but is not necessarily required to explain the drop.

Moreover, a very good description of the 1H 0707–495 data can be obtained by assuming that the spectrum is reflection–dominated as a result of multiple reflections from different layers of material. This situation may be expected, for example, if the system is characterised by a high accretion rate and disc instabilities are strong enough to produce large density inhomogeneities in the disc. A multiple reflection model gives an extremely good description ($\chi^2_\nu = 287/303$) to the data and is able to reproduce the drop at 7 keV (Fabian et al. 2002b; Ross, Fabian & Ballantyne 2002). Within this model, the large value of the line EW is produced self–consistently together with the reflection continuum.

Multiple reflection models have not yet been tested on IRAS 13224–3809, while a reflection–dominated spectrum due to multiple reflection (from the ionised reflection models of Ross & Fabian 1993 and Ballantyne, Iwasawa & Fabian 2001) gives a reasonable fit to the broadband spectrum of IRAS 13349+2438 (Longinotti et al. 2003). Furthermore, this model self–consistently accounts for the edge and the line without the necessity to invoke phenomenological models (such as the smeared edge, see discussion above).

Gravitational light bending could also give rise to multiple reflections: the reflected spectrum is partly forced to return to the disc by the strong gravitational field of the central black hole. In this case the spectrum produced by the second reflection would be predominantly emitted in the innermost regions of the disc, where lensing is stronger and thus most of the returning radiation is con-

centrated. The effect of the returning radiation (from the disc to the disc itself) would produce a steeper emissivity profile in the inner regions of the accretion disc than in the outer and a further reddening/broadening of the iron line (and of the RDC).

However, the overall effect of multiple reflections on the spectrum is complex: the spectra due to multiple reflections qualitatively resemble those due to single reflection with slightly higher ionisation parameters and much higher iron abundances. In particular, the relative strength of the iron emission line is enhanced with respect to the case of a single reflection and, therefore, large values of the line EW such as those needed to explain the drops in 1H 0707–495 and IRAS 13224–3809 in terms of reflection can be obtained (Ross, Fabian & Ballantyne 2002).

5 APPLICATIONS TO GALACTIC BLACK HOLE CANDIDATES

Our model for the spectral variability of AGN can, in principle, be applied to Galactic Black Hole candidates (BHC) as well. Strong, broad iron lines have been found in several BHC (e.g. Martocchia et al 2002; Miller et al 2002a,b,c and 2003a,b; Miniutti, Fabian & Miller 2003), some of which suggest rapid spin. The lines are often seen when the source is in a very high or intermediate state. In particular, in the cases of GX 339-4 and XTE J1650–500, the broad, relativistic iron line is associated with a very steep emissivity profile on the accretion disc and a very small inner disc radius, suggesting that the illuminating source is centrally concentrated and that the central black hole is rapidly spinning[1], as we are assuming in this work. Thus, these X–ray sources might represent laboratories to test our model in stellar mass black hole accreting systems.

A recent analysis based on *BeppoSAX* data of the XTE J1650–500 very high state evolution during its 2001 outburst, reveals that the (broad) iron line variability with respect to the observed PLC matches well the predictions of the light bending model (Miniutti et al. 2003). The same qualitative behaviour is also found in the long–term analysis of the *RXTE* data by Rossi et al. (2003; 2004, in preparation). The PLC decreases by about one order of magnitude during the outburst evolution, while the iron line drops only by a factor 3 following, with some scatter, the behaviour shown in Fig 2 during regimes I and II. The scatter could be introduced by the (here not modelled) variation in the power law photon index (that affects the iron line flux because the spectral shape of the illuminating continuum on the disc changes), or by intrinsic luminosity variations of the primary source. Moreover, the spectrum of XTE J1650–500 in the *BeppoSAX* data appears to become more and more reflection–dominated as the PLC decreases, again in excellent agreement with the predictions of the light bending model.

We also note that the iron line during the 2002 outburst of 4U 1543–47 shows a similar behaviour and seems to follow the path shown in Fig.2 (with some scatter and exceptions that could be due also to the observed intermittent radio activity during the outburst; see Park et al. 2003).

It would be remarkable if a simple model, such as the one we are proposing here, could account for some (if not most) of the spectral variability in some AGN as well as in a Galactic BHC such as XTE J1650–500 during its very high state evolution. Further observational study of the evolution of power law and thermal components and, if present, RDC and broad iron lines in BHC is needed to assess the relevance of light bending in these sources and to disentangle relativistic effects from different, obviously present, physical mechanisms. Due to the similarities between XTE J1650–500 and GX 339–4, we suggest that the very high state evolution in these two BHC could be similar and characterised by a drop of the PLC associated with an increase of the reflection fraction and with broad iron line variability according approximately to Fig. 2.

It is not our purpose to explain the behaviour of BHC here, but merely note that some of the observed variability may be accounted for by the strong light bending effects discussed here. Some of the extreme variability (see again, e.g. XTE J1650–500; Tomsick et al. 2003) could for example also be due to light bending effects that can occur on very short timescales in low–mass systems (see Section 3.3).

We point out here that broad iron lines are seen in AGN such as NGC 4051 and MCG–6-30-15 whose power spectral density (PSD) shows remarkable common features with that of the BHC Cyg X-1 in its high rather than low state (Vaughan, Fabian & Nandra 2003; Markowitz et al. 2003; M^{c}Hardy et al. 2003). Furthermore a power law spectral component is seen most of the time in the high state of Cyg X-1, making this state more similar to the very high state of other BHC, where both a thermal and a power law component are present (see M^{c}Clintock & Remillard 2003; Pottschimdt et al. 2003). Broad iron lines in BHC, as mentioned, are often observed in intermediate (e.g. Miller et al. 2002c) or in very high states (e.g. Miller et al. 2002a, Miniutti, Fabian & Miller 2003). We support therefore previous claims (see e.g. M^{c}Hardy et al. 2003) of a similarity between BHC in these states and AGN such as NGC 4051 and MCG–6-30-15, suggesting a possible geometrical origin for such a similarity (i.e. the presence of a centrally concentrated primary source close to the central black hole).

6 DISCUSSION AND CONCLUSIONS

We have explored a light bending model (Fabian & Vaughan 2003; Miniutti et al. 2003) in which the observed flux is strongly correlated with the height (h_s) of the primary X–ray source above the accretion disc around a massive black hole. High observed fluxes correspond to large h_s while if the source height is small (few gravitational radii) light bending forces most of the primary emission to be bent onto the disc dramatically reducing the flux and enhancing the reflection features.

Even without invoking intrinsic luminosity variation (likely to be present both on short and long timescales) changes of more than one order of magnitude in the direct continuum flux can be produced by light bending alone. Variability induced by light bending can act on such short timescales that even the large and fast variability of some NLS1 galaxies (e.g. IRAS 13224–3809) could be explained without breaking the "efficiency limit".

The reflection–dominated component (RDC) is variable with much smaller amplitude than the direct continuum (PLC) and three different regimes can be identified in which the RDC is correlated, anti–correlated or almost independent with respect to the direct continuum. These regimes correspond to low, high, and intermediate flux states respectively. As a general rule, the iron line EW is anti–correlated with the continuum and becomes almost constant only during very low or very high flux states.

At low fluxes (low source height) the spectrum becomes naturally reflection–dominated because of light bending so that large

[1] Or, if the black hole is slowly/non rotating, that the contribution from the plunging region is not negligible.

values of the reflection fraction are expected during particularly low flux states. Furthermore the reflected radiation as well can only partly escape the strong gravitational field of the central black hole and some returns to the disc producing multiple reflection from the inner regions of the disc and reddening the observed spectrum. Multiple reflections could also account for large values of the iron line EW, because the overall spectra strongly resemble those due to single reflection but with much higher iron abundance.

Low flux states are expected to be associated with broad iron emission lines. However, it is possible that the line is in some cases so broad (and weak) that chances of detection with current instruments are seriously compromised. Moreover, the ionisation of the inner regions of the disc (likely if the source height is small) may contribute to reduce the red wing of the line and to lower further the chances of detection.

The emission from the disc (and from the primary source) is also strongly beamed in the equatorial plane due to gravitational lensing and special relativistic beaming. One thus expects an additional reflection component from the outer regions of the disc (if the disc is flared and diverge from the equatorial plane) and/or the putative molecular torus. Both components should produce narrow features in the spectra that would be enhanced during low flux states, although depending on the particular source geometry. We thus predict a general anti–correlation between the EW of the narrow lines and X–ray flux (that could be related to the observed X–ray Baldwin effect). The beaming of the emission along the equatorial plane may be relevant also to the properties of the narrow optical emission lines in NLS1 galaxies. Due to the anisotropy of the illumination, the BLR appear as if they were flattened in the equatorial plane. An observer at low or moderate inclination would then detect narrow optical emission lines.

The light bending model proves able to account for many of the puzzling properties of MCG–6-30-15. In particular, if one interprets the low flux state of MCG–6-30-15 as regime I, the normal state as regime II and the high state as regime III, the following observational facts are fully recovered by our model (see also Miniutti et al. 2003):

(i) the timescale for the variability of MCG–6-30-15 is totally consistent with the capabilities of the model;

(ii) in normal flux states, MCG–6-30-15 is well described by a two–component model comprising a variable PLC (within a factor ~ 4) and an almost constant RDC and iron line (regime II);

(iii) the iron line profile of MCG–6-30-15 in normal flux states is well represented by a typical profile from regime II. The emissivity of the disc is in the form of a broken power law, steeper in the inner disc than in the outer;

(iv) the iron line EW in normal flux states is anti–correlated with the continuum, as we predict for regime II;

(v) in low flux states, the line appears to be broader, correlated with the continuum and an almost constant EW is observed (regime I);

(vi) the spectrum of MCG–6-30-15 appears to be more and more reflection–dominated as the flux decreases

(vii) in high flux states (regime III or II/III), the iron line appears to be generally narrower than in lower flux states (regime I or I/II).

All these properties are very well reproduced by our model and represent different, and mostly observationally independent, tests for any theoretical attempt to explain the MCG–6-30-15 spectrum and variability. The consistent behaviour of line flux, line EW, line profile, and relative strength of disc reflection with respect to the PLC variations strongly suggests that general relativistic effects in the near vicinity of the central (likely rotating) black hole provide an important contribution to the variability and that light bending is a relevant aspect of the overall picture.

Moreover, the NLS1 galaxy NGC 4051 exhibits spectral and variability properties that could also be explained by gravitational bending of the primary X–ray emission, even in the most extreme cases such as the ultra–dim and completely reflection–dominated spectrum observed in 1998. Possibly more remarkable (for the different mass scale with respect to MCG–6-30-15) is the behaviour of the Galactic black hole candidate XTE J1650–500 whose broad, relativistic iron line exhibits qualitatively the same variability behaviour as predicted by the light bending model during regimes I and II. These results suggest that the model we are proposing may well act in both supermassive and stellar mass black holes.

The variability of some black hole systems (in some epochs, such as the very high state, for BHC) could then be dominated by changes in the primary source height resulting in an average positive correlation between the RDC (and iron line) and the continuum if the source is in a low flux state (regime I or I/II), in an almost constant RDC/line if the source is in an intermediate flux state (regime II) and in anti–correlation in high flux states (regime II/III or III). Additional variability is likely to be provided by intrinsic luminosity variations, changes in the motion of the primary source and/or the presence of multiple emitting regions that are active at different times and locations (or heights). The ionisation structure of the surface of the accretion disc, which we have neglected for simplicity, can also be relevant and slightly modify our predictions.

However, we have shown that relativistic effects such as light bending can not be neglected, especially if some indication of a centrally concentrated primary source is found in observations (e.g. a steep emissivity profile, a broad iron line ...). The location (ρ_s , h_s) of the primary source represents an additional parameter that should be included in the analysis of the spectral variability. The light bending model provides a simple explanation for the properties of some X–ray sources and may well produce the bulk of the observed variability reconciling, in many cases, observations with theoretical models for reflection from accretion discs. It is also clear that a combination of light bending and intrinsic luminosity variations would cover a larger parameter space and could be relevant to interpret the spectral variability of many more sources than discussed in this work.

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